Physica E 56 (2014) 102–106

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Influence of phonon confinement on the optically-detected electrophonon resonance line-width in cylindrical quantum wires

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HIGHLIGHTS

- Absorption power is calculated taking into account the phonon confinement effect.
- Optically detected electrophonon resonance line-width (ODEPRLW) as profiles of curves is determined.
- The ODEPRLW increases with increasing temperature and decreases with increasing wire's radius.
- The ODEPRLW in the case of confined phonons is greater than it is in the case of bulk phonons.
- The influence of phonon confinement is very small and can be neglected for wires with large radii.

ARTICLE INFO

Article history:
Received 7 April 2013
Received in revised form
2 August 2013
Accepted 19 August 2013
Available online 29 August 2013

Keywords:
Line-width
Absorption power
Cylindrical quantum wire
Optically-detected electrophonon resonance

ABSTRACT

We investigate the effect of phonon confinement on the optically-detected electrophonon resonance (ODEPR) effect and ODEPR line-width in cylindrical quantum wires. The ODEPR conditions as functions of the wire's radius and the photon energy are also obtained. The shifts of ODEPR peaks caused by the confined phonon are discussed. The numerical result for the GaAs/AlAs cylindrical quantum wire shows that in the two cases of confined and bulk phonons, the line-width (LW) decreases with increasing wire's radius and increases with increasing temperature. Furthermore, in the small range of the wire's radius ($R \leq 30$ nm) the influence of phonon confinement plays an important role and cannot be neglected in reaching the ODEPR line-width.

1. Introduction

The absorption line-width (LW) is well-known as a good tool for investigating the scattering mechanisms of carriers and, hence, can be used to probe electron–phonon scattering processes. To investigate the effects of various scattering processes, absorption line-widths (LWs) have been measured in various kinds of semiconductors, such as quantum wells [1–6], quantum wires [7–10], and quantum dots [11–15]. These results show that the absorption LW has a weak dependence on temperature and has a strong dependence on system size. However, in those articles, the absorption LW was investigated based on the interaction of electrons and bulk phonons, the absorption LW in cylindrical quantum wires (CQWs) due to the confined-LO-phonon–electron interaction is still open for study.

A CQW is formed by a cylindrical wire of material one (such as GaAs) whose length is very much larger than radius, embedded in material two where the band-gap is much larger than it is in material one (such as AlGaAs). Carriers are confined in material one where the potential well develops by the band-gap difference between two materials. In this structure, phonon confinement is an essential part of the description of electron–phonon interactions [16]. It causes the increase of electron–phonon scattering rates [17–19] and significant nonlinearities in the dispersion relations of acoustic-phonon modes, and modifies the phonon density of states [20]. The polaronic states may be affected by changes in the Frohlich Hamiltonian caused by phonon confinement [21]. Since the early experimental observations of confined phonons [22,23], phonon modes in low-dimensional structures have been attracting much attention [16,24]. There have been many models dealing theoretically with phonon modes, such as

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1386-9477/$ - see front matter
http://dx.doi.org/10.1016/j.physe.2013.08.019

the hybridization theory, the Huang-Zhu model, the dielectric continuum model (see Ref. [21] and references therein). Phonon confinement is shown to be important whenever the transverse dimensions of a quantum wire are smaller than the phonon coherence length [16] and should be taken into account in order to obtain realistic estimates for electron–phonon scattering in low-dimensional structures [25–27]. Phonon confinement affects the optically-detected electrophonon resonance (ODEPR) effect mainly through changes in the selection rules for transitions involving subband electrons, and affects the ODEPR line-width (ODEPRLW) through changes in the probability of electron–phonon scattering. The LW is defined by the profile of curves describing the dependence of the absorption power (AP) on the photon energy or frequency [28,29]. Recently, our group has proposed a method, called the profile method, to computationally obtain the LW from graphs of the AP [30], and we used this method to determine the cyclotron resonance LW in CQWs [31] and in GaAs/AlAs quantum wires [32].

In the present work, we investigate the intersubband ODEPRLW in a CQW. We study the dependence of the ODEPRLW on the wire's radius and the temperature of system. The results of the present work are fairly different from the previous results because the phonon confinement is taken into account and because the results can be applied to optically detect the resonant peaks. The paper is organized as follows: calculations of analytic expression of the AP in CQWs taking into account the phonon confinement effect are presented in Section 2. The graphic dependence of the AP on the photon energy in the GaAs/AlAs CQW is shown in Section 3. From this dependence, we obtain the LW and examine the dependence of the LW on temperature and wire's radius. Finally, remarks and conclusions are shown briefly in Section 4.

2. Absorption power in a cylindrical quantum wire

Let us consider a cylindrical GaAs wire of radius R and length L ($L \gg R$) embedded in AlAs. Under the infinitely deep well approximation, the electron wave function can be written as [33]

$$\psi_{\ell j,k_z}\left(\vec{r}\right)=\frac{e^{ik_z z}}{\sqrt{L}}D_{\ell j}J_\ell\left(x_{\ell j}\frac{r}{R}\right)e^{i\ell\phi}, \quad (1)$$

with the corresponding energy

$$E_{\ell j}(k_z)=\frac{\hbar^2k_z^2}{2m_e}+\frac{\hbar^2(x_{\ell j})^2}{2m_eR^2}, \quad (2)$$

where $\ell=0,\pm1,\pm2,\ldots,\ j=1,2,3,\ldots,\ \vec{r}=(r,\phi,z)$ are the cylindrical coordinates for the system and k_z denotes the axial wave-vector component. $D_{\ell j}=1/(\sqrt{\pi}y_{\ell j}R)$ is the normalization factor, $x_{\ell j}$ is the jth zero of the ℓ th order Bessel function, i.e., $J_\ell(x_{\ell j})=0$ and $y_{\ell j}=J_{\ell+1}(x_{\ell j})$, and m_e is the effective mass of electron.

When an electromagnetic wave characterized by the time-dependent electric field of amplitude E_0 and angular frequency ω is applied to this system along the r-direction, the AP delivered to the system, $P(\omega)$, is given by [34]

$$P(\omega)=(E_0^2/2)\ \mathrm{Re}\{\sigma_r(\omega)\}, \quad (3)$$

where "Re" denotes "the real part of", $\sigma_r(\omega)$ is the r-component of the optical conductivity tensor. This component can be written further in a tangible form using the projection method on the linear response scheme as [35,36]

$$\mathrm{Re}\{\sigma_r(\omega)\}=e^2\sum_{\alpha,\beta}|j_r^{\alpha\beta}||r_{\alpha\beta}|\frac{(f_\beta-f_\alpha)\gamma_{\alpha\beta}(\omega)}{[\hbar\omega-(E_\beta-E_\alpha)]^2+[\gamma_{\alpha\beta}(\omega)]^2}, \quad (4)$$

here e is the charge of a conduction electron, $E_\alpha\equiv E_{\ell_\alpha j_\alpha}(k_z^\alpha)$ and $E_\beta\equiv E_{\ell_\beta j_\beta}(k_z^\beta)$ are the energies of the initial and the final states, $f_\alpha\equiv f(\ell_\alpha,j_\alpha,k_z^\alpha)$ being the Fermi–Dirac distribution function for an electron at the state $|\alpha\rangle$, $r_{\alpha\beta}$ and $j_r^{\alpha\beta}$ are the matrix elements of the position operator and the current operator, respectively, given by

$$|r_{\alpha\beta}|=\langle\alpha|r|\beta\rangle=\frac{(2\pi)^2}{\pi R^2L}\delta_{k_z^\beta k_z^\alpha}\delta_{\ell_\alpha\ell_\beta}N_{\ell_\alpha j_\alpha\ell_\beta j_\beta}(R), \quad (5)$$

$$\left|j_r^{\alpha\beta}\right|=\left|\left\langle\alpha,k_z^\alpha\left|\frac{ie\hbar\,\partial}{m_e\partial r}\right|\beta,k_z^\beta\right\rangle\right|=\frac{4i\pi e\hbar}{m_eR^2L}\delta_{k_z^\beta k_z^\alpha}\delta_{\ell_\alpha\ell_\beta}M_{\ell_\alpha j_\alpha\ell_\beta j_\beta}(R). \quad (6)$$

In these expressions, it is difficult to determine the explicit forms of the matrix elements $N_{\ell_\alpha j_\alpha\ell_\beta j_\beta}(R)$ and $M_{\ell_\alpha j_\alpha\ell_\beta j_\beta}(R)$ for arbitrary states. So, in the following calculation we will only make use of the radial wave function for the ground state employed recently by Masale and Constantinou [37] and Gold and Ghazali [38]. The component $\gamma_{\alpha\beta}(\omega)$ in Eq. (4) is called the damping term [35,36] and is given by the following equation:

$$\begin{aligned}\gamma_{\alpha\beta}(\omega)(f_\beta-f_\alpha)&\\ =\pi\sum_{\mu,q}|C_{\beta\mu}(q)|^2&\Big\{[(1+N_q)f_\alpha(1-f_\mu)\\ &-N_qf_\mu(1-f_\alpha)]\delta(\hbar\omega-E_\mu+E_\alpha-\hbar\omega_q)\\ &+[N_qf_\alpha(1-f_\mu)-(1+N_q)f_\mu(1-f_\alpha)]\delta(\hbar\omega-E_\mu+E_\alpha+\hbar\omega_q)\Big\}\\ +\pi\sum_{\mu,q}|C_{\alpha\mu}(q)|^2&\Big\{[(1+N_q)f_\mu(1-f_\beta)\\ &-N_qf_\beta(1-f_\mu)]\delta(\hbar\omega-E_\beta+E_\mu-\hbar\omega_q)\\ &+[N_qf_\mu(1-f_\beta)-(1+N_q)f_\beta(1-f_\mu)]\delta(\hbar\omega-E_\beta+E_\mu+\hbar\omega_q)\Big\},\end{aligned} \quad (7)$$

here $\delta(\ldots)$ is the Dirac's delta function; N_q is the Planck distribution function for a phonon in the state $|q\rangle=|m,n,q_z\rangle$; $\omega_q^2=\omega_0^2-\gamma^2(q_{mn}^2+q_z^2)$ where ω_0, γ, q_z are, respectively, the zone-center LO phonon frequency, the velocity parameter (4.73×10^3 m s^{-1} for GaAs [39]), the wave vector of phonon along the wire axis; and $C_{\beta\mu}(q)$ is the matrix elements of electron–phonon interaction and depends on the scattering mechanism. In this model, it is given by

$$C_{\beta\mu}(q)=C_{mn}(q_z)I_{\ell_\beta j_\beta\ell_\mu j_\mu}(q_{mn})\delta_{k_z^\beta,k_z^\mu+q_z}, \quad (8)$$

where [33,40]

$$I_{\ell_\beta j_\beta\ell_\mu j_\mu}(q_{mn}R)=2\int_0^1\xi\,d\xi\frac{1}{y_{\ell_\beta j_\beta}y_{\ell_\mu j_\mu}}J_\ell\left(x_{\ell_\beta j_\beta}\xi\right)J_{|\ell_\beta-\ell_\mu|}(q_{mn}R\xi)J_{\ell_\mu}\left(x_{\ell_\mu j_\mu}\xi\right), \quad (9)$$

$$|C_{mn}(q_z)|^2=\frac{\pi e^2\hbar\omega_0}{2VJ_{m+1}^2(x_{mn})}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\frac{1}{q_{mn}^2+q_z^2}, \quad (10)$$

with $q_{mn}R=x_{mn}$ [41], $V=\pi R^2L$ is the volume of the quantum wire, χ_0 and χ_∞ are the static and high-frequency dielectric constants, respectively.

To obtain a detailed expression for the AP, we need to calculate $\gamma_{\alpha\beta}(\omega)$ in Eq. (7) and then substitute it into Eqs. (4) and (3). To do this, we change the summations over q and μ into integrals as

$$\sum_q\to\frac{L}{2\pi}\sum_{m,n}\int_{-\infty}^{+\infty}dq_z,\quad \sum_\mu\to\frac{L}{2\pi}\sum_{\ell_\mu j_\mu}\int_{-\infty}^{+\infty}dk_z^\mu. \quad (11)$$

Also, the power absorption in the system for the transition between the two lowest sublevels is simply calculated at the band edge ($k_z^\alpha=0$). Note that the selection rule requires $k_z^\alpha=k_z^\beta$ or a direct transition. After some mathematical manipulation, we have

$$\begin{aligned}\gamma_{\alpha\beta}(\omega)\left[f_\beta-f_\alpha\right]&\\ =\sum_{\ell_\mu j_\mu}\sum_{m,n}&\left\{\frac{|I_{\ell_\mu j_\mu\ell_\beta j_\beta}|^2}{(Q_1^2+q_{mn}^2)Y^{(-)}(Q_1,q_{mn})}\right.\\ &\times\left[(1+N_q)f_{\ell_\alpha j_\alpha,0}\left(1-f_{\ell_\mu j_\mu,Q_1}\right)-(1+N_q)f_{\ell_\mu j_\mu,Q_1}\left(1-f_{\ell_\alpha j_\alpha,0}\right)\right]\end{aligned}$$